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Experimental Investigations on the Distortion of ISAR Images using Different Radar Waveforms

S. Wong, E. Riseborough and G. Duff

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Abstract

Experimental results have shown that the Inverse Synthetic Aperture Radar (ISAR) image of a target can be distorted severely as a result of a small perturbing motion possessed by the target. This has been observed regularly in radar images of moving targets such as in-flight aircraft, ships sailing on high seas and maneuvering ground vehicles. A Target Motion Simulator apparatus that simulates a target with small perturbing motion has been designed and built to study the ISAR distortion experimentally. A series of measurements under controlled conditions have been conducted to collect the distorted ISAR image data. Two different radar waveform types, pulse compression and stepped frequency, are used in this investigation. The purpose of the experiment is to determine whether the radar waveform also plays a role in the distortion of ISAR images. A systematic analysis has been carried out to characterize the resulting ISAR distortion from images generated by both types of waveforms. Results indicate that the distortion is independent of the radar waveform used. This information will be useful for developing image refocusing procedures to restore distorted ISAR images for target identification applications.

Résumé

L'image d'une cible fournie par le radar à synthèse d'ouverture inverse (ISAR) peut être déformée en raison d'un faible mouvement perturbateur de cette cible. Ce phénomène a été observé régulièrement dans l'imagerie radar de cibles en mouvement telles que des aéronefs en vol, des navires navigant en haute mer et des véhicules terrestres exécutant des manœuvres. On a conçu et construit un simulateur de mouvement de cible qui reproduit une cible animée d'un faible mouvement perturbateur dans le but d'étudier expérimentalement la distorsion des images ISAR. On a effectué une série de mesures dans des conditions contrôlées afin de recueillir des données relatives aux images ISAR déformées. Les résultats de l'expérience montrent qu'un faible mouvement perturbateur de la cible peut causer une importante distorsion des images ISAR. Deux types de signaux radar différents, soit les signaux à impulsions comprimées et les signaux à fréquences échelonnées, sont utilisés dans l'étude. Le but visé est de déterminer si le type de signal radar joue un rôle dans la distorsion des images ISAR. On a effectué une analyse systématique dans le but de caractériser la distorsion des images ISAR. Les résultats montrent que la distorsion est indépendante du type de signal radar utilisé. Cette information sera utile pour l'élaboration de procédures permettant de refaire la mise au point des images en vue de corriger les images ISAR déformées dans les applications d'identification de cibles.

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Executive summary

Inverse Synthetic Aperture Radar (ISAR) is a Non-Cooperative Target Recognition (NCTR) technique that is currently being investigated for target identification in the Combat ID community. ISAR provides a 2-dimensional radar image of a moving target. The ability to identify moving targets makes ISAR an attractive operational radar mode for surveillance radar systems such as those installed on board of the CP-140 long-range patrol aircraft, air defence radar systems such as the Active Phased Array Radar (APAR) designed for the Canadian Patrol Frigates and the ADAT low-level air-defence systems for the Army.

The maneuvering nature of moving targets, such as in-flight aircraft, can produce severe distortion in the ISAR images of the targets. Data from aircraft measurement trials have shown that a significant fraction of the ISAR images collected are distorted beyond use for identification. It is necessary to develop a fuller understanding of how other factors can affect the distortion in the imaging process. Corrective procedures can then be developed accordingly to properly compensate for any influence that may affect the imaging process. Earlier experimental and numerical works have shown that severe distortion can be generated by small perturbation in the target's motion. Another relevant factor that could play an influential role in ISAR distortion is the radar waveform used to acquire the ISAR image. The purpose of this study is to determine whether the radar waveform plays a role in affecting the distortion.

An experimental apparatus, Target Motion Simulator, was designed and built to simulate a target that possesses a small perturbing motion. Controlled experiments are conducted to study the distortion characteristics in ISAR images using two different types of radar waveforms. Data from these measurement trials allow analytical characterization of the distortion. This information will be useful for developing signal processing procedures to restore distorted ISAR images. For example, it may be necessary to take the radar waveform into account as a factor in the image restoring process.

A series of experimental measurements are made using a pulse compression waveform and a stepped frequency waveform to investigate the ISAR distortion process. These two radar waveforms are commonly used in operational military radar systems. Results indicate that the distortion is independent of the radar waveform. Rather, the distortion is strongly dependent on the change of the target's Doppler motion during the image integration period. This implies any refocusing process can be based on the physics of the target's motion alone, without having to take the radar waveform into account as a factor. This makes the refocusing procedure simpler and universally applicable to different radar waveform types used.

This study is a part of the work sponsored by the US Office of Naval Research to investigate the distortion of ISAR images under the US Navy's International Collaborative Opportunity Program (NICOP). Canada is a participant in this project on "Time-frequency processing for ISAR imaging and Non-Cooperative Target Identification". The work performed in this report is relevant to the ISAR imaging capability of the surveillance radar systems on-board of the CF C-140 Aurora patrol aircraft. It should also be noted that target recognition based on radar imagery will play an important role in future CF initiatives on ISR for land, air and maritime applications.

Wong, S., Riseborough, E., Duff, G. 2003. Experimental Investigations on the Distortion of ISAR Images using Different Radar Waveforms. DRDC Ottawa TM 2003-196. Defence R&D Canada - Ottawa.

Sommaire

L'identification de cibles est une fonction essentielle pour les systèmes de commandement et de contrôle. L'identification fiable des cibles ennemies est essentielle dans les missions de surveillance et dans les situations de combat. Même si elles sont déjà utilisées pour identifier les cibles amies, les techniques de coopération, par exemple l'identification ami ou ennemi, ne permettent pas l'identification certaine des cibles ennemies et des cibles neutres. On considère que les techniques de reconnaissance de cibles non coopératives (NCTR) constituent des solutions possibles pour l'identification fiable des cibles ennemies. En outre, l'identification des cibles fera partie intégrante d'une nouvelle approche pour la gestion des données relatives à l'espace de combat, comme les nouvelles initiatives de renseignement, surveillance et reconnaissance (RSR). La capacité d'identifier les cibles permettra aux Forces canadiennes d'obtenir une meilleure connaissance de la situation de l'environnement entourant l'espace de combat, d'engager rapidement des cibles potentiellement menaçantes et de réduire le risque de tir fratricide en conditions de combat. En somme, l'identification des cibles, particulièrement en mode de non-coopération, jouera un rôle important dans les applications RSR.

On étudie actuellement la possibilité d'utiliser le radar à synthèse d'ouverture inverse (ISAR), un outil de reconnaissance de cibles non coopératives (NCTR), pour l'identification des cibles dans la collectivité de l'identification de combat. L'ISAR fournit une image radar bidimensionnelle d'une cible en mouvement. En raison de sa capacité d'identifier les cibles en mouvement, le radar ISAR est un outil opérationnel intéressant pour les systèmes de surveillance radar, comme ceux qui sont installés à bord de l'avion de patrouille à long rayon d'action CP-140, pour les systèmes radar de défense aérienne, comme le radar à balayage électronique actif (APAR) conçu pour les frégates canadiennes de patrouille, et pour les systèmes de défense aérienne à basse altitude ADAT de l'Armée de terre.

Les images ISAR obtenues pour les cibles en mouvement exécutant des manœuvres, par exemple les aéronefs en vol, peuvent présenter une grande distorsion, ce qui gêne le processus d'identification. Il est nécessaire de comprendre de manière plus approfondie comment d'autres facteurs peuvent contribuer à la distorsion dans le processus d'imagerie. Des mesures de correction pourront alors être élaborées en conséquence pour compenser adéquatement tout effet exercé sur le processus d'imagerie. Un facteur évident qui pourrait contribuer à la distorsion des images ISAR est le signal radar utilisé pour l'acquisition de ces images. La présente étude vise à déterminer si le type de signal radar contribue à la distorsion.

Le simulateur de mouvement de cible, un appareil expérimental, a été conçu et construit pour reproduire une cible animée d'un faible mouvement perturbateur. On effectue des expériences contrôlées pour étudier les caractéristiques de distorsion des images ISAR en utilisant deux types différents de signaux radar. Les données recueillies dans ces essais de mesures permettent de caractériser analytiquement la distorsion. Elles seront utiles pour l'élaboration de procédures de traitement des signaux permettant de corriger les images ISAR déformées. Par exemple, il pourrait être nécessaire de considérer le signal radar comme un facteur du processus de correction des images.

On effectue une série de mesures expérimentales en se servant d'un signal à impulsions comprimées et d'un signal à fréquences échelonnées pour étudier le processus de distorsion des images ISAR. Ces deux types de signaux radar sont couramment utilisés dans les systèmes radar militaires opérationnels. Les résultats montrent que la distorsion est indépendante du type de signal radar, mais qu'elle dépend beaucoup de la variation du mouvement Doppler de la cible durant la période d'intégration de l'image. Par conséquent, tout processus destiné à refaire la mise au point de l'image peut être basé sur la physique du mouvement de la cible seulement, sans qu'il soit nécessaire de tenir compte du type de signal radar. Ainsi, la procédure servant à refaire la mise au point est plus simple et applicable universellement à différents types de signaux radar utilisés.

Cette étude fait partie des travaux parrainés par l'*Office of Naval Research* des États-Unis visant à étudier la distorsion des images ISAR dans le cadre du *International Collaborative Opportunity Program* de la marine américaine (NICOP). Le Canada participe au projet sur le traitement temps-fréquence d'imagerie ISAR et d'identification de cibles non coopératives (*Time-frequency processing for ISAR imaging and Non-Cooperative Target Identification*). Les travaux décrits dans le présent rapport ont trait à la capacité d'imagerie ISAR des systèmes radar de surveillance installés à bord de l'avion de patrouille Aurora CP-140 des FC. Il faudrait aussi souligner que la reconnaissance des cibles basée sur l'imagerie radar jouera un rôle important dans les initiatives futures des FC portant sur l'utilisation du RSR dans les applications terrestres, aériennes et maritimes.

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Acknowledgements

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1. Introduction

Inverse Synthetic Aperture Radar (ISAR) imaging provides a 2-dimensional image of a target. ISAR images can be used as target signatures for non-cooperative target recognition. Since ISAR imaging relies on the target's own motion, small random fluctuations in the target's motion can introduce severe distortion to the ISAR images[1]. For example, small time-varying perturbed pitch, yaw or roll motion from fast maneuvering aircraft can lead to smearing in the images[2]. Figure 1a and 1b show two ISAR images of an in-flight aircraft that were taken in a consecutive sequence in time. The image on the left is relatively well focused and the image on the right is severely blurred. The blurred image is attributed to the time-varying motion of the aircraft during imaging. The time-varying motion can be seen from the time-frequency spectrograms of the target as shown in Figure 1. The spectrograms provide a glimpse of the aircraft's temporal motion. When the target's motion is steady, the spectrogram displays a constant Doppler frequency as a function of time; this is

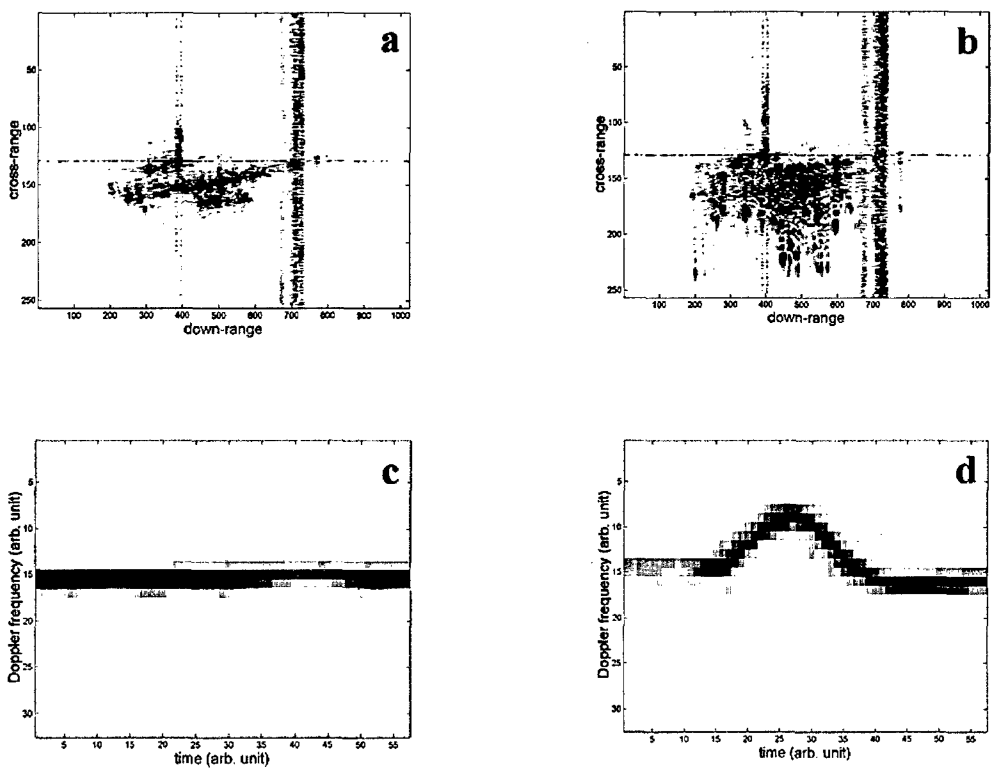


Figure 1 Experimental ISAR images of an in-flight aircraft. a) a relatively well focused image. b) a distorted image. c) spectrogram of the target's Doppler frequency as a function of time for the focused image. d) spectrogram for the distorted image. Both A and B were taken in a consecutive sequence in time.

shown in Figure 1c. When the target possesses a small perturbing motion, a fluctuating Doppler frequency is seen in the spectrogram; this is shown in Figure 1d. It has been observed in a NATO aircraft signature measurement trial that over 30% of the ISAR images of the aircraft collected are found to be distorted[3]. The degradation in the aircraft images is severe enough that the images are deemed un-usable for target recognition. However, there has been very little work to date describing how target motion affects the quality of the ISAR images quantitatively and in particular, whether radar waveform as a system parameter plays any role in the distortion of ISAR images.

To obtain a better understanding of the distortion in ISAR images, image data have to be collected under controlled conditions so that proper analysis can be carried out to provide a better insight on the distorting mechanism. It is very difficult to conduct a definitive study on the distortion phenomenon using in-flight aircraft. There is no precise information on the target's rotational motion and no a priori knowledge of the intrinsic target image for comparison. To overcome these problems, we have devised an experiment to study the distortion in ISAR images.

A Target Motion Simulator (TMS) apparatus was designed and built, allowing the study of the distortion effect in ISAR images under controlled experimental conditions. This experimental apparatus enables us to simulate a small time-varying fluctuating motion on a target. It allows us to conduct controlled experiments where the rotational rate and the fluctuating motion of the target can be pre-determined. The objective is to demonstrate that a gross distortion can occur in the target's ISAR image as a result of small fluctuating motion. A series of measurement data from the TMS have already been used to verify the simulated results from a numerical model that was developed to model the distortion process[4]. The validated numerical model has provided us with a deeper insight and a better understanding into the physical process of distortion in ISAR images.

The TMS also allows us to obtain an intrinsic, undistorted ISAR image of a target as reference for comparing with distorted images of the target. Furthermore, the TMS offers a common reference with reasonably reproducible motion that permits us to conduct comparative studies on the distortion of ISAR images using different radar waveforms. In contrast, it is much more difficult trying to get an in-flight aircraft to reproduce similar temporal motion in a series of measurements.

It is imperative to determine whether the radar waveform plays any role in the distortion process. It may be necessary that the radar waveform be taken into account as a factor in the refocusing process of distorted ISAR images. A series of experiments has been conducted using the TMS to collect distorted ISAR image data from two different radar waveforms, e.g., pulse compression waveform and stepped frequency waveform. A characterization of the distorted ISAR images is then given to provide an overall view of the distortion obtained from each of the two radar waveforms.

2. ISAR Imaging Formation

An ISAR image is produced first by generating a temporal sequence of High Range Resolution (HRR) profiles of the target. A HRR profile provides a 1-dimensional radar image of the scattering centers of the target along the radar's line of sight; i.e., the down-range direction. The second dimension of the ISAR image is created when a sequence of HRR profiles is processed by a second Fourier transform to separate scatterers that coincide at the same down-range location but have different Doppler frequencies. This creates the cross-range direction of the ISAR image.

Basically, an ISAR image is generated from a sequence of M consecutive High Range Resolution (HRR) profiles. Each HRR profile has N down-range bins. Assuming the HRR profiles are range aligned and phase aligned among one another, a Fourier transform is performed at each of the down range bin of the M HRR profiles to generate the cross-range bins. A matrix of M x N elements of cross-range and down-range bins are thus obtained. The amplitude of each matrix element forms the intensity pixel of a 2-dimensional ISAR image.

High resolution ISAR images require wideband radar waveforms. The two most commonly used radar waveforms that meet the bandwidth requirement for ISAR imaging is the chirp-pulse compression waveform and the stepped frequency waveform. Regardless of the type of waveform, the achievable down-range resolution is given by[5]

$$\Delta r_d \approx \frac{c}{2\beta} \tag{1}$$

where β is the effective radar bandwidth and c is the speed of light. The cross-range resolution is given by[5],

$$\Delta r_c = \frac{c}{2f}\frac{1}{\omega_c}\frac{PRF}{M} \tag{2}$$

where PRF is the pulse repetition rate of the HRR sequence, $PRF/M = 1/T$ and T is the image integration time; ω_c is the rotational rate of the target. The corresponding unambiguous range window for both the chirp-pulse compression and stepped frequency waveforms can be shown to be given by[5]

$$r_d = \frac{c}{2\Delta f} \tag{3}$$

where Δf is the frequency step size in the case of the stepped frequency waveform and in the case of the chirp-pulse compression waveform, it is the required frequency spacing for unambiguous sampling in the frequency domain in the Nyquist's Theorem for sampling [5]. The unambiguous cross-range window is given by

$$r_c = \frac{c}{2f}\frac{1}{\omega_c}PRF \tag{4}$$

Given that each individual HRR profile can be imaged in a relatively short duration, the distortion of an ISAR image occurs in the cross-range direction in which the integration time over a sequence of HRR profiles can be relatively long, e.g., a few seconds. The distortion has been shown to be a consequence of Doppler fluctuation in the phase of the echo over the ISAR image integration time[4]. This Doppler induced distortion in the cross-range direction has also been observed from in-flight aircraft imaging measurements and has been predicted in numerical simulation. This is known as the phase modulation effect[4].

In the stepped frequency waveform, the HRR profile of a single-point target has the form[5],

$$g(t) = A\frac{\sin\left(\frac{N}{2}2\pi\Delta f t\right)}{\sin\left(\frac{1}{2}2\pi\Delta f t\right)}\exp(j2\pi f_c t) \tag{5}$$

The corresponding ISAR image formed from the sequence of stepped frequency HRR profiles images is given by,

$$s_t(f) = \int_{-\infty}^{\infty} g(\tau(t))\exp(-j2\pi f\tau)d\tau \tag{6}$$

where N is the number of frequency steps, Δf is the frequency step size, f_c is the center frequency of the stepped frequency waveform bandwidth, t is the sampling time along the HRR down-range direction, and τ is the sampling time along the cross-range direction where the temporal sequence of HRR profiles is sampled and time integrated in forming the ISAR image. In the pulse compression waveform, the form of the HRR profile is given by[6],

$$h(t) = \sqrt{\frac{\mu T_1^2}{2\pi}}\exp(j\frac{\pi}{4})\frac{\sin(\mu T_1^2 t)}{\mu T_1^2 t}\exp(j2\pi(f_c t + \frac{\mu}{2}t^2)) \tag{7}$$

The ISAR image is expressed as,

$$p_t(f) = \int_{-\infty}^{\infty} h(\tau(t))\exp(-j2\pi f\tau)d\tau \tag{8}$$

where T_1 is the duration of the compressed pulse, μ is the frequency sweep rate given by β/T_1 (i.e., pulse bandwidth/pulse duration).

Note that the phase of the complex HRR profile is linear in time for the stepped frequency waveform (Equation (5)) and is quadratic in time for the pulse compression waveform (Equation (7)). The purpose of the study conducted in this report is to determine experimentally whether the form of the phase of the radar waveform has any effect on the behaviour of the distortion in the ISAR images. As mentioned above, the distortion is a consequence of the modulation effect in the phase of the return radar signal from the target.

3. Description of the Target Motion Simulator

To study the distortion in ISAR images, a delta-wing shaped target motion simulator (TMS) is designed and built. This apparatus is capable of generating a time-varying rotational motion so that the distortion in the ISAR images can be investigated. A picture of the TMS is shown in Figure 2. The TMS measures 5m on each of its three sides. Six trihedral corner reflectors are mounted on the TMS to provide known scattering centers on the target. Each reflector has a length of 0.5 m on its two orthogonal sides of the triangular panels, providing a radar cross-section of about 23 dBsm at a radar frequency of 10 GHz. All six reflectors are connected by a set of belts pulleys such that when the target is rotating, all six reflectors turn synchronously and remain pointing towards the radar at all times. The rotational motion of the TMS is provided by a computer programmable motor. It can rotate at a constant rotational speed to provide undistorted ISAR images. A time-varying oscillating motion can be superimposed on the constant rotation to produce a small perturbing motion. This fluctuating motion produces a blurred ISAR image of the target.

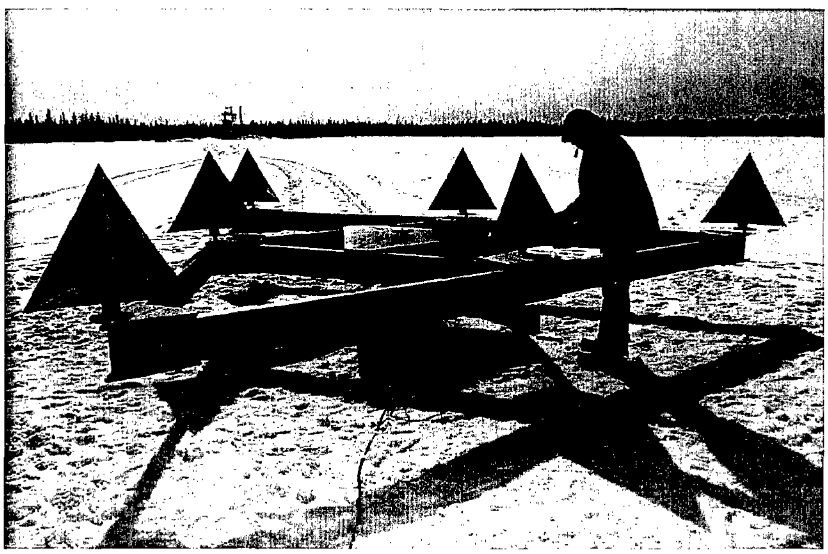


Figure 2 A photograph of the delta-wing shaped Target Motion Simulator apparatus.

For a real target such as an in-flight aircraft, the fluctuating motion is random in nature. A random motion can be fully described by a Fourier series,

$$g(t)=\sum_{n}\left(a_n\cos\left(2\pi v_n t\right)+b_n\sin\left(2\pi v_n t\right)\right) \tag{9}$$

where a_n, b_n and v_n are random variables. For simplicity in generating the time-varying motion and in facilitating the analysis of the target's motion, only a single oscillating term from the Fourier series in Equation (9) is used; i.e.,

$$g(t)=A\sin\left(2\pi\Omega t\right) \tag{10}$$

where A is the rotational amplitude and Ω is the frequency of the oscillating motion. Thus the TMS has a time-dependent rotational motion given by

$$\omega(t) = \omega_0 + A\sin(2\pi\Omega t) \tag{11}$$

where ω_0 is the rate of constant rotation. The oscillating frequency is limited to a maximum of 1 Hz; this is constrained by the inertia of the target and the backlash in the gearing system of the drive mechanism that provides the oscillating motion. Figure 3 shows the angular displacement of the TMS as a function of time in an ideal scenario. The parameters used are ω_0 = 1.4 degrees/s, Ω = 1Hz and the amplitude A has a value that corresponds to a peak to peak displacement of 1 degree. The dashed line represents the constant rotational motion case and the solid line represents the case where the TMS has an additional sinusoidal motion simultaneously superimposed on the constant rotational motion.

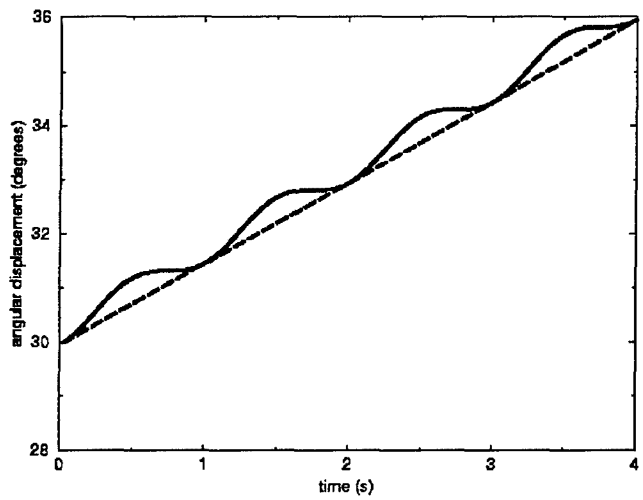


Figure 3 Angular motion of the Target Motion Simulator as a function of time. Dash line: constant rotation. Solid line: an oscillating motion superimposed on a constant motion.

4. Description of the Radar Facilities

Two experimental trials were conducted to investigate the ISAR distortion characteristics using two different radar waveforms. One trial was conducted in France during the NATO 068 task group's aircraft signature measurement trial in April 2003. The French research agency ONERA had provided their MERIC (Moyen Experimental pour la Reconnaissance et l'Identification des Cibles) radar for data collection.

MERIC is a fully polarimetric, high resolution radar operating at a centre frequency of 10.1 GHz and has a 300 MHz bandwidth. The radar employs a CW, FM-modulated pulse compression waveform operating at a PRF of 2 kHz. The waveform generator has 8 bit resolution samples, D/A converter with 450 MHz external clock and real time waveform monitoring. The high range resolution (HRR) data are obtained using a matched filter, de-ramping using a Z transform. Each HRR profile is generated in 0.5 ms (i.e., 1/PRF).

The second trial was conducted at DRDC-Ottawa using the EARS (Experimental Array Radar System). The EARS radar employs a stepped frequency radar waveform. The radar operates at frequencies from 8.9 to 9.4 GHz, providing a 500 MHz bandwidth. The large bandwidth is achieved synthetically by stepping through a band of frequencies. The radar frequency can be changed by a discrete amount through a frequency synthesizer. The size of the frequency steps (Δf) can be varied. The maximum rate of the frequency step change is 2 kHz. For a frequency step size of 10 MHz, it takes 50 frequency steps to provide a 500 MHz bandwidth. Thus it requires 25 ms to generate a single HRR profile, i.e., an effective HRR PRF of 40 Hz. The radar returns in the frequency domain are converted into in-phase and quadrature (I,Q) components. A Fourier transform is then performed on the in-phase and quadrature signals to generate a HRR profile.

As a note of interest, ISAR imaging using stepped frequency waveform is most applicable to phased array radar system. Most of the next generation military radars will likely be phased array systems. However, phased array systems have an inherently narrow instantaneous bandwidth. A synthetic wide bandwidth can be obtained through the use of the stepped frequency radar waveform, offering a solution to the wide bandwidth requirement in imaging applications.

5. Characterization of the ISAR Distortion

As stated in the introduction, the objective of studying the distortion experimentally is to determine what influence the radar waveforms have on the distortion characteristics in ISAR images. Information on any differences in the distortion characteristics due to different radar waveforms will be invaluable for developing refocusing procedures to correct the distorted ISAR images. For example, if a certain distortion characteristic is observed in one type of waveform but not in another, then an appropriate procedure has to be developed to refocus the distorted images properly, tailoring to a given radar waveform type.

Distorted ISAR images are characterized in a comparative study between the pulse compression waveform and the stepped frequency waveform, using a common set of criteria. The distortion is analyzed by first extracting the temporal motion of the target using a time-frequency spectrogram. The ISAR images are then processed at different temporal intervals of a fixed duration. The amount of distortion in the ISAR images are then compared between different integration intervals to see whether there is any correlation between the amount of distortion and the amount of change in the Doppler frequency, and between the amount of distortion and the duration of the image integration time.

5.1 French Trial

The ISAR imaging experiments using a pulse compression waveform were conducted in conjunction with the NATO SET068 Technical Task Group's aircraft radar signature measurement campaign at a French air base in Salon-de-Provence, France. The TMS was placed approximately 2 km from the radar. A schematic of the experimental set-up is shown in Figure 4. The TMS was initially rotating at a constant rate of 1.4 degrees per second for about 10 seconds. Then, an oscillating motion at about 1 Hz was superimposed onto the constant rotation. Since the TMS was stationary, i.e., no radial translational motion along the radar's line of sight, no range alignment between HRR profiles was needed in forming the ISAR images. The only adjustment required was the centering of the HRR profiles in the down range direction such that the processed ISAR image was centered in the viewing window.

Figure 5a shows an undistorted ISAR image of the TMS target. The six trihedral corner reflectors can be seen clearly. The ISAR image appears a bit compressed in the cross range (vertical) direction because there are 35 range bins in the vertical direction, compare to only 25 down-range bins in the horizontal direction. The size of the cross-range bins is about the same as that for the down-range bins, i.e., $\Delta r_d \approx \Delta r_c$. The reason why a larger number of cross-range bins is used in Figure 5 is to allow a large enough viewing window in the cross-range so that the blurring will not be aliased. This viewing window set-up helps to better facilitate the comparison between the undistorted and distorted images of the target, providing a clearer illustration of the distorting effect. As an illustration, Figure 5b shows a distorted ISAR image of the target possessing an oscillating motion.

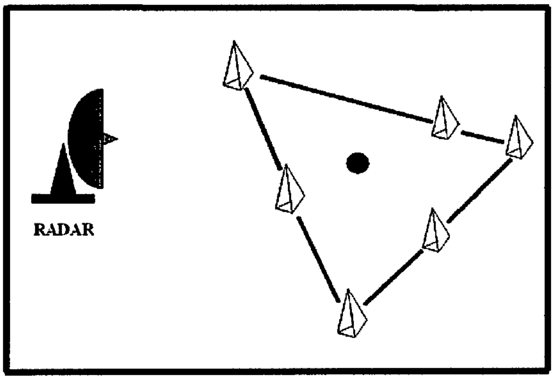


Figure 4 A schematic of the ISAR imaging experimental set-up.

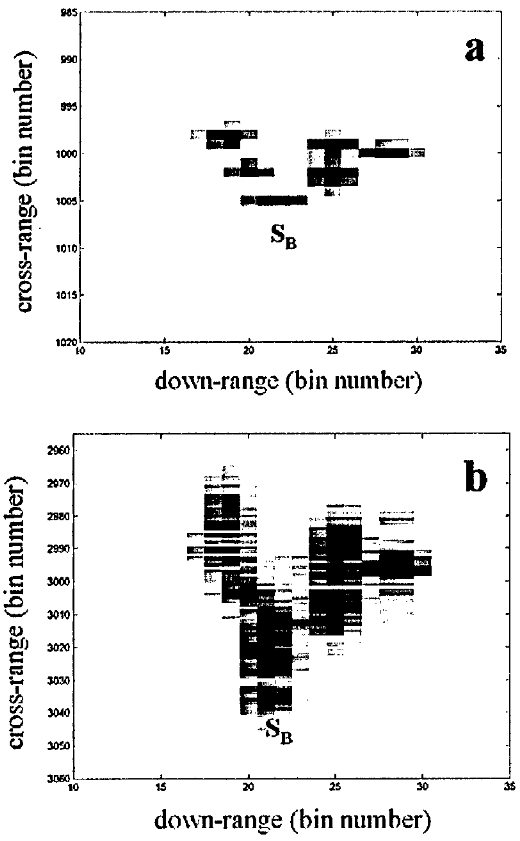
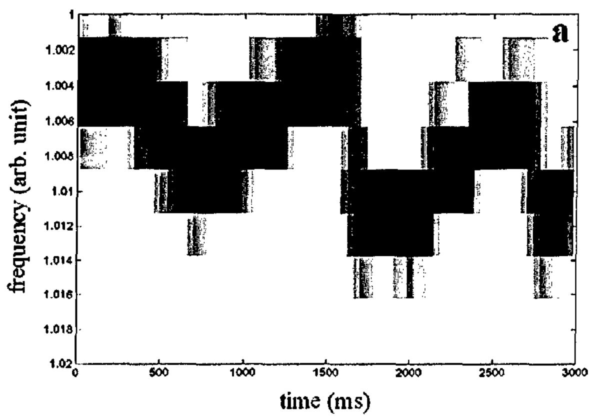


Figure 5 ISAR images of the Target Motion Simulator. a) undistorted image, b) distorted image.

To characterize the distorted ISAR image due to the target's time-varying motion, it is necessary to first extract the actual temporal motion of the target. This is achieved by computing a time-frequency spectrogram on a selected scatterer on the target. In this case, the scatterer S_B in Figure 5b was selected to compute the spectrogram. The resulting temporal motion of the scatterer is shown in Figure 6a. By assuming that the target behaves like a rigid body, the motion of one of the scatterers on the target serves as a good indicator of the motion of the target as a whole. The spectrogram provides information on the Doppler frequency (i.e., target motion) as a function of time. In essence, it displays the instantaneous angular rotational rate of the target. A digitized trace of the target's temporal motion is shown in Figure 6b. It can be seen that the actual oscillating sinusoidal motion is somewhat deformed. This is due to the fact that the rotational inertia of the TMS is quite considerable; moreover, there is backlash in the gearing system of the apparatus. The unevenness in the amplitude of the oscillation shown in Figure 6 can be attributed to the fact that it would be more



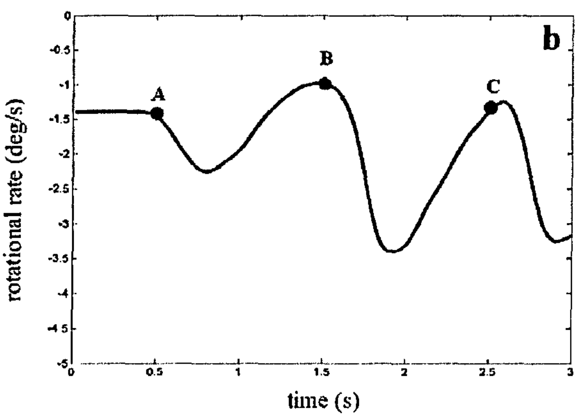


Figure 6 a) a time-frequency spectrogram of the Target Motion Simulator's temporal motion, b) a digitized trace of the motion taken from the spectrogram in a).

difficult initially to overcome the inertia of a constant rotational motion in forcing the apparatus into an oscillating mode. But once the apparatus is in the oscillating mode, then it is easier for the apparatus to follow the input sinusoidal drive signal more truly. This explains why the amplitude of the first oscillating cycle is smaller than the subsequent one in Figure 6. It has been checked and confirmed from the measured data that the subsequent oscillations at later time are uniform both in amplitude and frequency.

The ISAR images are processed at different temporal intervals of a fixed duration using the temporal motion of the target as shown in Figure 6. Figure 7 shows two ISAR images, one is processed from A to B and the second one is processed from B to C along the target's motion. Both ISAR images have an image integration time of 1 second. However, it can be seen that the amount of distortion is different between the two ISAR images. A more interesting and contrasting result is observed in Figure 8. Two ISAR images, one with an integration time of 3 seconds and the other one with an integration time of 1 second, exhibit the same amount of distortion. Note that the two ISAR images are different in appearance. This is because the 3-second ISAR image has three times higher cross-range resolution than the 1-second ISAR image.

Empirically, we have arrived at two observations from the experimental data. Firstly, ISAR images with the same imaging duration can have different amount of distortion. This is illustrated in Figure 7. The two ISAR images both have a 1-second image integration time. But the amount of distortion is different in each image. Secondly, the amount of distortion is independent of the ISAR imaging time. As illustrated in Figure 8, the 3-second image is temporally integrated through considerably more motion variation of the target than the 1-second image. But there is no apparent time accumulative effect in the distortion. Both ISAR images are distorted the same amount.

It has been shown from numerical analysis[5] that the size of the distortion is directly related to the amount of change in the Doppler motion during the image integration period. That is, the severity of the distortion depends on the amplitude of the fluctuating motion; i.e., Δf_D the change in the Doppler frequency in Figure 6a. Thus the distortion in the top image in Figure 7 is less severe than the one in the bottom image because the change in the Doppler frequency during the duration from A to B is less than that from B to C. A further confirmation that the amount of distortion is related to the amount of change in the Doppler frequency is illustrated in Figure 8. The distorted ISAR image processed using an image integration time of 3 seconds has the same amount of distortion as the distorted image using only 1second of image integration time. This is because both images contain the same maximum Doppler frequency change Δf_D during their respective image integration period. From the observations illustrated in Figures 7 and 8, it can be summarized that the distortion is dependent on the amount of maximum Doppler change within the image integration duration. The length of the image integration duration has no effect on the distortion.

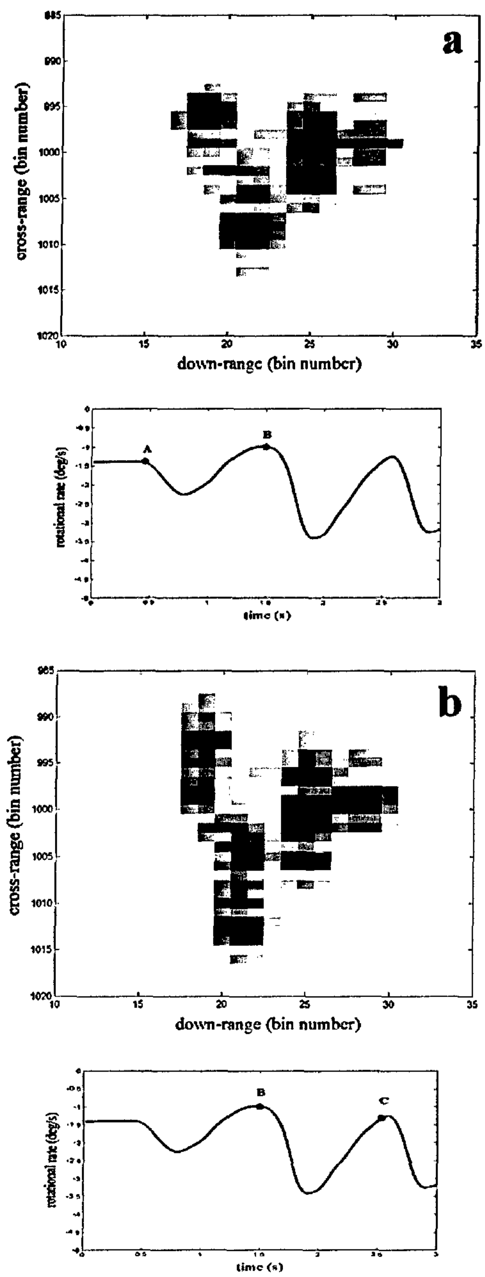


Figure 7 Distorted ISAR images processed at different time intervals. a): 1-second image integration from A to B. b): 1-second image integration from B to C along the Target Motion Simulator's temporal motion.

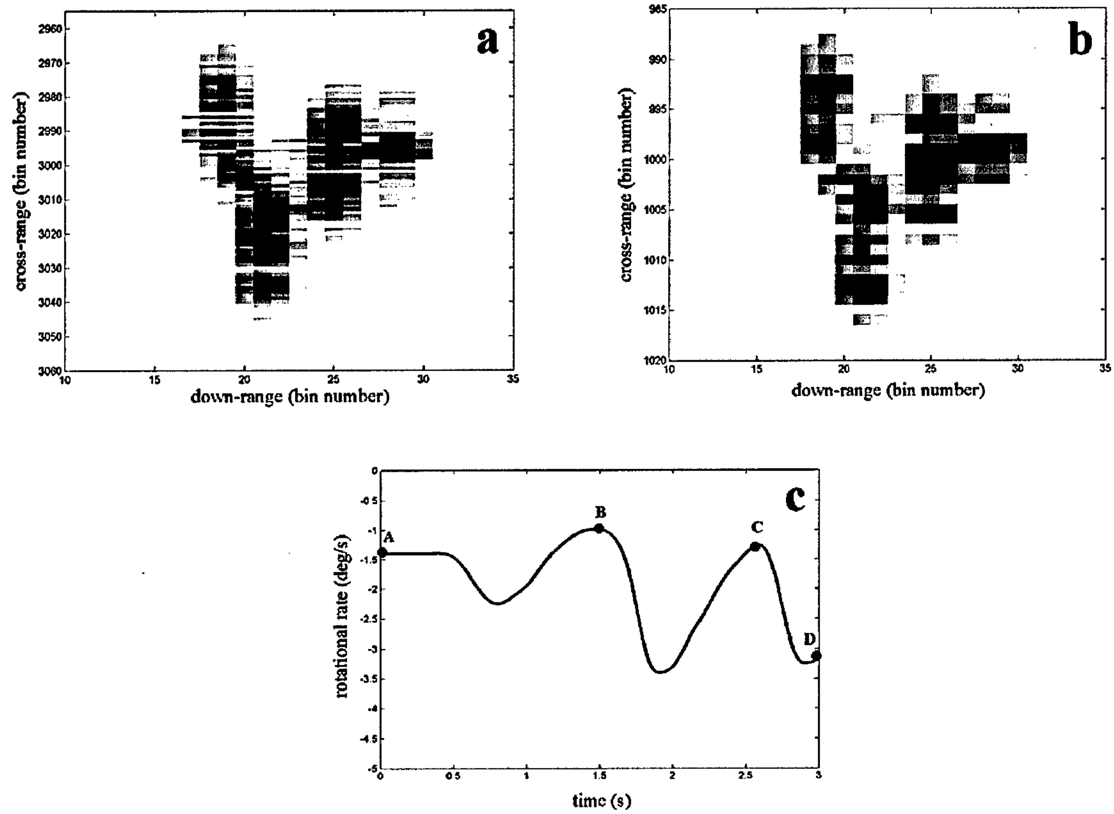


Figure 8 Distorted ISAR images processed using different image integration durations. a) image integration time =3 seconds (A to D). b) image integration time = 1 second (B to C). c) temporal history of the TMS's motion.

5.2 DRDC-Ottawa Trial

A second set of ISAR imaging experiments using a stepped frequency waveform was conducted at DRDC-Ottawa. The TMS experimental set-up was identical to that in the French trial. The target was placed approximately 800 m from the radar. This closer placement of the target was due to a lack of available space at the DRDC-Ottawa site, comparing to the much larger open space at the French air base. The motion sequence of the TMS for data collection was the same as in the French trial. Figure 9 shows a sequence of ISAR images of the target. The TMS was initially rotating at a constant speed of 2.2 degrees/s (Figure 9a). At some instant in time, an oscillating motion of 0.5 Hz was introduced to the target and the ISAR image was starting to become blurred (Figure 9b). As the oscillating motion continued, more severe distortion was induced in the ISAR image; this is shown in Figure 9c and Figure 9d at two instants of time sequentially.

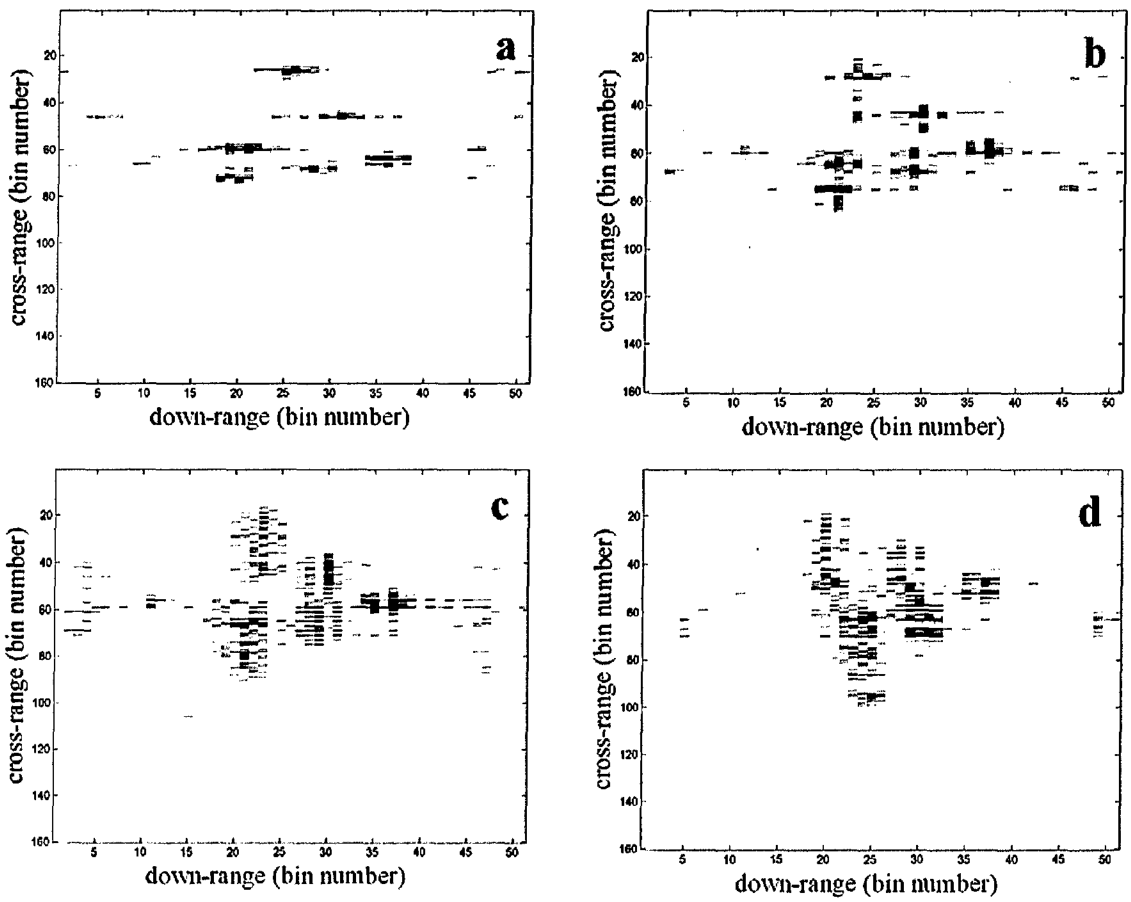


Figure 9 A sequence of ISAR images illustrating the distortion at different instants in time.

Each ISAR image is processed using 4 seconds of integration time; i.e., 160 HRR profiles. The temporal motion of the target is extracted using the time-frequency spectrogram; this is shown in Figure 10. The motion in the spectrogram corresponds to the scatterer in down-range bin 20 of the ISAR image in Figure 9d. To characterize the distortion, two ISAR images are processed from the motion as shown in Figure 10. One is processed from the time interval A to B and the second one is processed from B to C. The two ISAR images are shown in Figures 11a and 11b respectively. Both have an image integration time of 2 seconds. As seen in Figure 10, the amount of change in the Doppler frequency is the same in both durations; therefore, the amount of distortion in both images is expected to be the same. This is indeed shown to be the case as illustrated in Figures 11a and 11b. Furthermore, the amount of change in the Doppler motion during the entire 4-second duration is the same as each of the 2-second durations. The target has gone through the same maximum amount of Doppler motion change in the 4-second interval. The only difference is that it has gone through the same Doppler change twice. Thus the ISAR image with the 4-second integration time would have the same amount of distortion as the two ISAR images with 2-second of integration time. This is illustrated in Figure 11c. The comparison of the distorted ISAR images in Figure 11 clearly demonstrates that the distortion in the ISAR image is dependent on the maximum amount of Doppler motion change during the image integration period and not dependent on the length of the integration period. This result is identical to that obtained using the pulse compression waveform in Section 5.1.

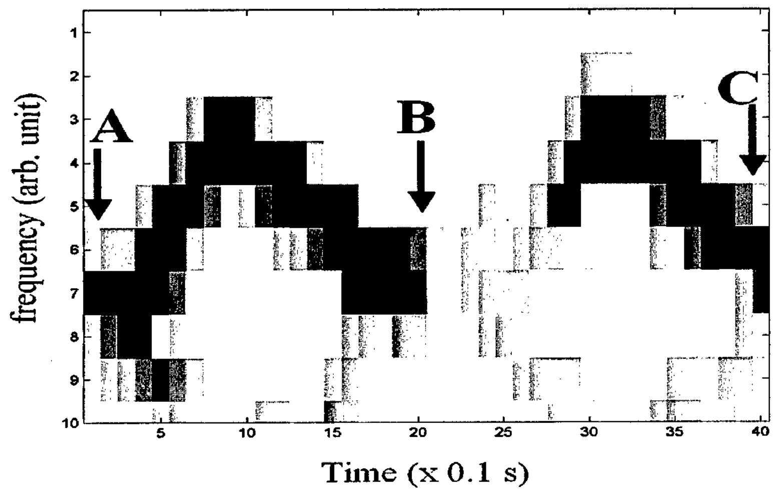


Figure 10 A time-frequency spectrogram of the temporal history of the Target Motion Simulator's motion.

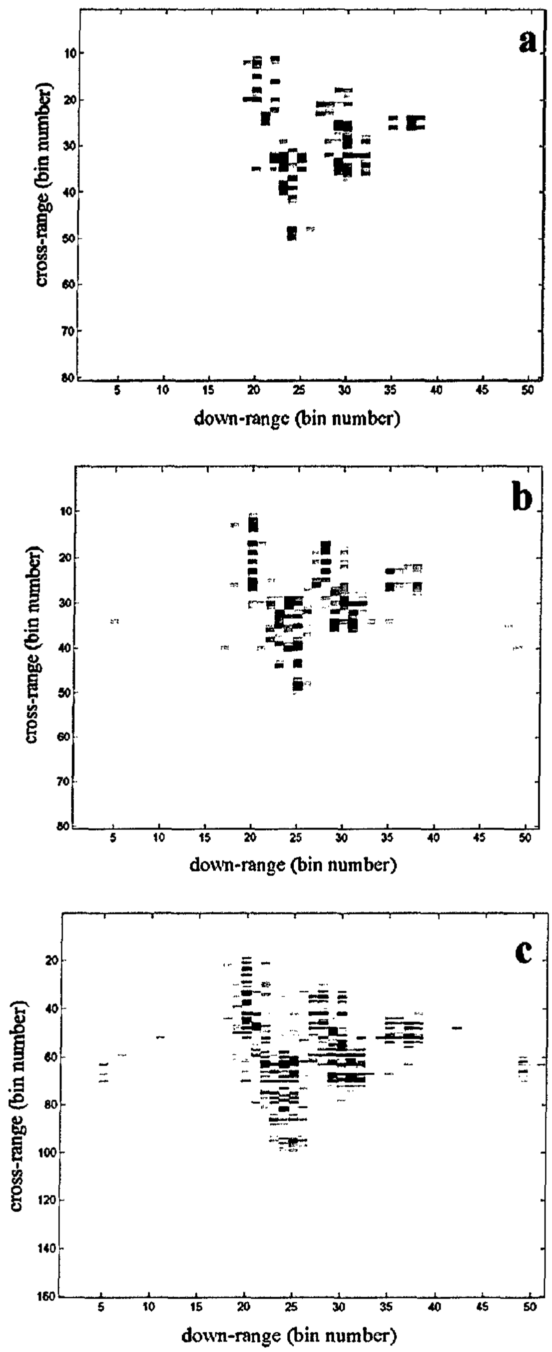


Figure 11 Distorted ISAR images from different time intervals as given in Figure 10.
a) A to B, b) B to C, c) A to C.

6. Conclusion

Pulse compression and stepped frequency radar waveforms are capable of providing wide bandwidth and therefore they are commonly employed in radar imaging applications. This report presents a quantitative experimental investigation of the ISAR imaging process, using both radar waveforms. A series of experiments has been conducted to investigate the distortion characteristics in ISAR images. Results from the experiments indicate that the amount of distortion that appears in the ISAR image is not dependent on the image integration time.

The experimental data offer clear evidence that ISAR images can get distorted severely when the target is subjected to a small perturbing motion. The amount of distortion in the ISAR image is found to relate directly to the amount of change in the Doppler frequency experienced by the target during the image integration period. This is known as the phase modulation effect[5]. In essence, the fluctuating target motion introduces a non-linear effect in the phase of the radar return signal, resulting in the distortion of the ISAR image.

The phase of the radar waveform is responsible for the formation of the ISAR images by coherent image processing. Although the phase of different radar waveforms can have different time dependence, for example, linear in time in stepped frequency and quadratic in time in pulse compression, results obtained in this study indicate that ISAR distortion is dependent neither linearly nor quadratic in time. Hence, it can be concluded that the type of radar waveform used does not play any role in the distortion process.

For target recognition applications, the blurred ISAR images have to be refocused to provide usable images for identification. The results from this study suggest that the ISAR distortion process can be described based on the physics of the target's motion, without having to take the radar waveform into consideration. This makes the refocusing process of distorted ISAR images simpler and universal to different radar waveforms used.

The work described in this report addresses a fundamental question on the ISAR imaging process, in particular, regarding the radar waveforms deployed in various radar systems. The experimental results have provided a definitive answer that is of considerable technical interest and is useful for implementing image-refocusing procedures. This work is especially relevant to the ISAR imaging capability of the surveillance radar systems on-board of the CF CP-140 Aurora patrol aircraft and the US Navy's P3 Orion surveillance aircraft. Moreover, target recognition based on radar imagery will play an active role in future CF initiatives on ISR (Intelligence, Surveillance and Reconnaissance) for land, air and maritime applications.

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